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White striping, woody breast and spaghetti meat: Cooccurrence and relationship with breast fillet weight in big broiler chicken flocks

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Abstract: The present study aimed to determine the incidence and coincidence of white striping (WS), woody breast (WB) and spaghetti meat (SM) in raw chicken breast meat (n = 300) collected 3–3.5 h *post mortem* from commercial broiler flocks (Ross 708 males, 56 days of age). The fillets were scored for the occurrence and severity of WS, WB and SM using visual and tactile methods, and the relationship between myopathies and breast weight was evaluated. A total of 88% of samples (out of 300) had either one or a combination of three myopathies, leaving only 12% without any myopathies. Approximately 29% of the fillets had only one myopathy present, with 59% of the samples demonstrating the cooccurrence of breast myopathies. In the present study, 47.7% of WB samples also exhibited WS, while the cooccurrence of WB and SM was exhibited in 14.7%. Based on binomial logistic regression, an increase in WB scores decreases the odds that the fillet may be affected by SM myopathy. No association was found between SM and fillet weight. Multinomial logistic regression showed that the weight of breast fillets was positively associated with WB1 (P = 0.011), WB2 (P < 0.001), and WB3 (P < 0.001). Furthermore, positive associations were found between WS1 and WB3 (P = 0.004) as well as between WS2 and WB3 (P < 0.001). The percentage distribution changes of each WB and WS myopathy score were used in relation to the 10 weight groups. The percentages of WB3 increased and WB0 decreased as the average fillet weight increased. Regarding linear regression, these results exhibited a positive linear relationship for both WB (R^2 = 0.91, P < 0.001) and WS (R^2 = 0.71, P = 0.002) myopathy with fillet weight. A high prevalence of myopathies was observed. The incidence of severe WB categories and the overall high cooccurrence rate are alarming.

Keywords: fast-growing chickens; breast meat; myopathy; incidence; poultry

Intensive selection for fast growth, increased bird size, high breast yield, reduced production cost and improved processing efficiency has resulted in new muscle myopathies predominantly affecting the *pectoralis major* muscle in fast-growing meat-type modern broilers recorded over the past decade

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(Soglia et al. 2021). At least three myopathies have commonly been recognized in broiler breast muscle and are commonly referred to as white striping, woody breast and spaghetti meat, which have a negative impact on meat quality and customer acceptability leading to economic losses (Petracci et al. 2019). The situation is further complicated by the fact that breast meat is often affected by more than one myopathy with a diverse combination of severities (Che et al. 2022a).

The changes in breast muscle architecture due to myopathies influence the quality characteristics of raw and processed meat (Baldi et al. 2020). The basis of the changes in WS, WB and SM are pathological processes that have a number of common microscopic features, while the macroscopic manifestations are different (Petracci et al. 2019; Soglia et al. 2019). Baldi et al. (2020) indicated that hypoxia resulting from an imbalance between the amount of capillaries and muscle fibres is the basic triggering mechanism for the development of these muscle abnormalities. Insufficient oxygen supply and inadequate removal of metabolic waste products lead to the accumulation of reactive oxygen species, which results in the development of an inflammatory process associated with varying degrees of myodegeneration (Baldi et al. 2020). Gradually, as repair mechanisms are exhausted, necrosis of muscle fibres, oedema, fibrosis and lipidosis appear (Soglia et al. 2019; Baldi et al. 2020). White striations, as a typical macroscopic manifestation of WS defects, are caused by the proliferation of connective tissue and significant accumulation of lipids (Kuttappan et al. 2013). Polyphasic myodegeneration with fibrotic changes in the chronic phase microscopically characterizes WB myopathy, in which breast fillets are hard and pale in appearance (Sihvo et al. 2014). In general, the progressive rarefaction of the connective tissue in the endomysium and perimysium, as well as the presence of immature and newly formed connective tissue, are probably the essence of the poor muscle cohesion manifested in SM myopathy by the separation of the fibrous bundles forming the pectoral muscle (Baldi et al. 2018; Huang and Ahn 2018). Histopathological changes, i.e., the replacement of muscle fibres with connective and fat tissue, lead to a reduction in nutritional properties and physical characteristics. The impact on these quality traits and on consumers' willingness to pay depends on the severity of the myopathy and the possible cooccurrence in the same breast fillet (Baldi et al. 2020).

Over the last 13 years, studies have focused on various aspects, such as nutrition, genetics, and proteomics, associated with individual myopathies; limited work has been published on the cooccurrence of all three abnormalities with respect to their severity levels. The present study was aimed at investigating the prevalence of the cooccurrence of modern myopathies in big fast-growing broilers.

MATERIAL AND METHODS

Sample collection

The experiment was conducted in a federally inspected commercial chicken processing plant in Alabama, United States of America. Three flocks (all-male, Ross 708) raised to a live weight of approximately 3.5 to 4.0 kg were slaughtered and processed according to standard commercial practices at the age of 56 days. Chilled carcasses were manually deboned 3–3.5 h *post mortem*, and a total of 300 skinless and boneless breast fillets (100 fillets × three flocks or replications) were randomly selected from the deboning line. The left breast fillet samples were individually weighed and analysed for WS, WB and SM incidence.

Classification of white striping, woody breast and spaghetti meat

To minimize variability, the freshly deboned breast fillets were scored by one experienced person immediately after deboning. The breast fillets were evaluated visually for severity of WS based on the thickness and frequency of white lines and categorized as follows: 0 = no distinct white lines (normal); 1 = easily visible white lines on the breast surface but smaller than 1 mm (mild); 2 = very visible white lines (1 to 2 mm) on the breast surface (moderate); 3 = almost entire breast surface is covered with white bands thicker than 2 mm (severe) (Kuttappan et al. 2016). Fillets were hand-palpated to determine the degree of hardness and classified using the 4-point scale (Tijare et al. 2016) with 0 = no toughness or hardness throughout breast fillets (normal); 1 = hardness mainly in the cranial region but flexible otherwise (mild); 2 = extremely hard

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and rigid in the cranial region but flexible in mid to caudal region (moderate); 3 = extremely hard and rigid throughout the entire breast fillet, more than 50% of fillet area is woody (severe). SM myopathy was rated as absent (0) or present (1) based on visual and tactile analysis for myofibre separation in the cranial-ventral portion of the breast fillets. With respect to cooccurrence evaluation, all fillet samples received a compound score representing each myopathy degree and were divided into multiple categories in the range from WS0WB0SM0 to WS3WB3SM1.

To assess the relationships between individual scores of WS and WB myopathy and breast fillet weights, the samples were divided into 10 almost equal-sized groups (ca. 30 samples per group) based on breast sample weights (Table 1).

Statistical analysis

The statistical analysis was performed using SAS software (SAS v9.4, SAS Institute Inc., Cary, NC, USA) with significant differences at $P \leq 0.05$ for all analyses. Descriptive statistics were used to characterize the breast fillet weight distribution, weight groups of breast fillet samples, and WS and WB myopathy scores in the weight groups. Two logistic regression models were used to assess the associations between breast meat myopathies and fillet weights. In both regression models, unaffected breast fillets were set as the reference category.

The first model was used as a binomial logistic regression to predict a dichotomous dependent variable represented by SM myopathy based on WS, WB, and breast fillet weight as independent variables.

This model containing category SM present ($Y = 1$) and category SM absent ($Y = 0$) is defined by Formula 1:

$$\text{logit}(\pi) = \ln \frac{P(Y = 1 | X_1, X_2, \ldots, X_k)}{P(Y = 0 | X_1, X_2, \ldots, X_k)} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k \quad (1)$$

where:

$P(Y = 1 | X_1, X_2, \ldots, X_k)$ – expresses the probability of being at category SM present depending on the values of the independent variables $X_1, X_2, \ldots, X_k$;

β_0 – an intercept;

$\beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k$ – regression coefficients were estimated by the maximum likelihood (ML) method using the GENMOD procedure.

The second model was used as a multinomial logistic regression that allows the prediction of more categories (normal, mild, moderate, severe) of the dependent variable represented by WB myopathy based on multiple independent variables (WS, SM, breast fillet weight).

This model is defined by Formula 2:

$$\text{logit}(\pi_j) = \ln \frac{P(Y = j | X_1, X_2, \ldots, X_k)}{P(Y = 0 | X_1, X_2, \ldots, X_k)} = \beta_{j0} + \beta_{j1} X_1 + \beta_{j2} X_2 + \ldots + \beta_{jk} X_k \quad (2)$$

where:

j – becomes 1 = mild, 2 = moderate, 3 = severe;

β_{j0} – intercept for the jth category of dependent variable;

β_{jk} – the kth regression coefficient for the jth category of dependent variable.

To evaluate the probability, the multinomial logistic regression model was estimated by the maximum likelihood (ML) method using the LOGISTIC procedure. The results from the logistic regression analysis were described as the odds ratio (OR). To estimate the precision of the odds ratio, the 95% confidence interval (CI) and the respective P-value were used. Generally, OR > 1 suggests an increased chance, while OR < 1 denotes a decreased chance of a dependent category as a result of an increase in the independent variable by one unit. Linear regression analysis was used to evaluate the relationships between breast fillet weights and selected myopathies. This model was performed within each of the 10 established weight groups, where the mean myopathy score was calculated for each weight group.

Table 1. Descriptive statistics of fillet weight (g) in weight groups

Range of weight group (g)	n	Mean	Median	SD
340.1–394.0	30	371.01	369.05	16.795
394.1–424.0	30	407.40	407.10	9.913
424.1–442.0	31	433.51	434.20	5.003
442.1–461.0	31	453.94	454.40	5.268
461.1–474.0	30	468.13	469.30	3.799
474.1–492.0	28	481.81	480.40	6.206
492.1–504.0	30	497.20	496.50	3.587
504.1–533.0	30	518.91	516.65	8.408
533.1–570.0	30	548.36	545.65	11.406
570.1–667.5	30	599.73	595.60	23.643

n = number of observations; SD = standard deviation

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The model is defined by Formula 3:

$$Y = \beta_0 + \beta_1 X_1 \quad (3)$$

where:

β_0 – the intercept;
β_1 – the coefficient;
X – the explanatory variable;
Y – the dependent variable.

In this model, when X increases by one unit, Y will change by β_1. The least squares method using the PROC REG procedure was used to calculate the best-fitting line for the observed data.

RESULTS

Breast sample description

All three types of myopathies at different severity levels were observed among the evaluated breast fillets (Figure 1).

Fillets with WS defects had white lines parallel to muscle fibres predominantly in the cranial half of the breast samples, while those with WB myopathy had a tough region (tactile) and a pale appearance. Petechial haemorrhages in the cranial half were often present on the surface of the breasts in severe WB fillets. Fillets affected by SM myopathy showed a loss of muscle integrity in the cranial region with easily separable bundles of muscle fibres, and the meat was often soft or even mushy.

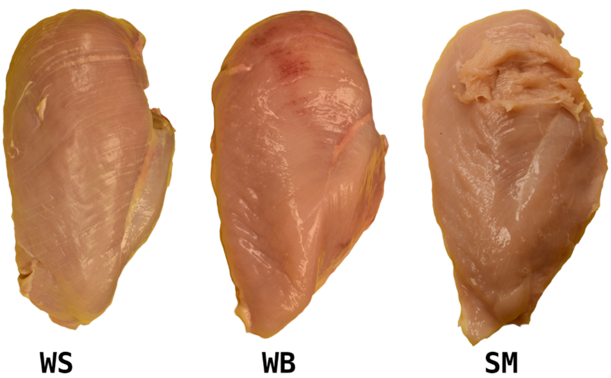

Figure 1. Breast fillets with muscle abnormality, i.e., white striping (WS), woody breast (WB) and spaghetti meat (SM)

WS myopathy (left) is characterized by clearly visible white stripes parallel to the muscle fibres, WB myopathy (centre) hardened muscle with visible signs of inflammation (swelling, petechiae); and, SM myopathy (right) with the extremely soft cranial region and the bundles of muscle fibres easily separable

The descriptive statistics of fillet weights are summarized in Table S1 in electronic supplementary material (ESM; for the ESM see the electronic version). The range of breast fillet weight varied from 340.1 to 667.5 g and showed a normal distribution (Figure 2).

Breast myopathy distribution and cooccurrence

Irrespective of cooccurrence and myopathy severity levels, the present study (300 breast fillets) revealed that 58.7% of breast fillets had WS, 72% had WB, and 25% had SM defects. In terms of WS severity levels, 41.3% were scored as 0 (normal), 37.7% scored as 1 (mild), 19.3% scored as 2 (moderate), and 1.7% scored as 3 (severe). Furthermore, the incidence of WB was 28% (normal), 21.3% (mild), 27.3% (moderate), and 23.3% (severe). Table 2 summarizes the cooccurrence of WS, WB and SM. Among the evaluated breast fillets (n = 300), only 12% of samples were not affected by any myopathy, while 29% of samples were affected by at least one myopathic condition, while 59% of samples exhibited the presence of more than one myopathy. The most common cooccurrence was observed for the WS2WB3SM0 (10.7%), WS1WB2SM0 (10%), and WS0WB2SM0 (9.3%) categories.

Associations between breast myopathies and fillet weight

The binomial logistic regression model was used to analyse the associations between SM myopathy and WB, WS and fillet weight (g). As indicated in Table 3, an increase in the WB score decreased the odds that the fillet may be affected by SM myopathy. Although no association was found between SM and WB1, a significant association was noted for SM and WB2 ($P < 0.001$), while the strongest association was found between SM and WB3 ($P < 0.001$). However, SM myopathy and WS1, WS2, WS3, and fillet weight were not significantly associated.

A multinomial logistic regression model was used to test associations between WB and SM, WS, and fillet weight (g), using WB0 as the reference category

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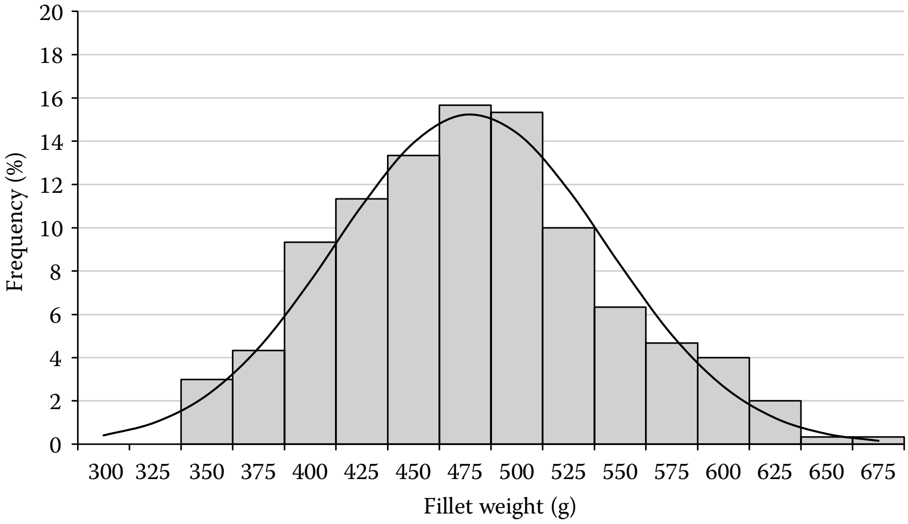

Figure 2. Distribution of fillet weights in 300 chicken breast samples

Table 2. Cooccurrence of white striping (WS), woody breast (WB), and spaghetti meat (SM) myopathy distribution in fillets (% of 300 fillets) sampled from three high breast-yielding male broiler (Ross 708) flocks

Myopathy levels	WB0		WB1		WB2		WB3	
	SM0	SM1	SM0	SM1	SM0	SM1	SM0	SM1
WS0	12	5	5.3	4.3	9.3	1.7	3.7	0
WS1	5	4	4.3	4.3	10	2	7.7	0.3
WS2	0.7	1.3	1.3	1.7	3.3	0.3	10.7	0
WS3	0	0	0	0	0.7	0	1	0

SM0 = SM absent; SM1 = SM present; WB0= WB normal; WB1 = WB mild; WB2 = WB moderate; WB3 = WB severe; WS0 = WS normal; WS1 = WS mild; WS2 = WS moderate; WS3 = WS severe

Table 3. Associations between spaghetti meat (SM) and woody breast (WB), white striping (WS) and fillet weight (g) performed on 300 breast fillet samples. It was modelling the probability that SM is present

	Odds ratio	95% CI		SE	*P*-value
		lower limit	upper limit		
Weight					
Increase 1g	1.01	1.00	1.01	0.003	0.072
WB					
WB1 vs WB0	1.34	0.67	2.66	0.469	0.407
WB2 vs WB0	0.22	0.10	0.50	0.092	< 0.001
WB3 vs WB0	0.02	0.00	0.12	0.016	< 0.001
WS					
WS1 vs WS0	1.46	0.77	2.75	0.473	0.242
WS2 vs WS0	1.36	0.52	3.56	0.668	0.533
WS3 vs WS0	ND	ND	ND	ND	ND

CI = confidence interval; ND = not detected; SE = Standard error; WB0 = WB normal; WB1 = WB mild; WB2 = WB moderate; WB3 = WB severe; WS0 = WS normal; WS1 = WS mild; WS2 = WS moderate; WS3 = WS severe

(Table 4). The association between each WB score and SM myopathy was similar to that reported above. Furthermore, the weight of breast fillets was positively associated with WB1 ($P = 0.011$), WB2 ($P < 0.001$), and WB3 scores ($P < 0.001$). The WS1 score was positively associated with the WB3 score ($P = 0.004$); however, no significant associations were found between the WS1 score and the WB1 and WB2 scores. Similarly, a significant association between the WS2 score and WB3 score was found ($P < 0.001$), but the WS2 and WB1 and WB2 scores were not associated.

Because spaghetti meat was scored by a simple presence/absence rather than severity levels and SM did not have any association with fillet weights, it was not considered for further analysis.

Distribution of WB and WS myopathy scores in the fillet weight groups

Established weight groups (Table 1) were used for a more detailed description of percentage distri-

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Table 4. Associations between woody breast (WB) and spaghetti meat (SM), white striping (WS) and fillet weight (g) performed on 300 breast fillet samples. It was modelling that WB0 (normal) is the reference category

Variable		Response	Odds ratio	95% Confidence interval		*P*-value
				lower limit	upper limit	
SM	SM1 vs SM0	WB1	1.279	0.641	2.552	0.485
		WB2	0.228	0.102	0.507	< 0.001
		WB3	0.019	0.002	0.149	< 0.001
Weight	increase 1 g	WB1	1.008	1.002	1.015	0.011
		WB2	1.013	1.007	1.019	< 0.001
		WB3	1.018	1.011	1.025	< 0.001
WS	WS1 vs WS0	WB1	1.481	0.719	3.050	0.287
		WB2	1.965	0.965	4.005	0.063
		WB3	3.995	1.565	10.203	0.004
	WS2 vs WS0	WB1	1.942	0.610	6.185	0.262
		WB2	2.118	0.667	6.727	0.203
		WB3	17.148	5.089	57.786	< 0.001
	WS3 vs WS0	WB1	ND	ND	ND	ND
		WB2	ND	ND	ND	ND
		WB3	ND	ND	ND	ND

ND = not detected; SM0 = SM absent; SM1 = SM present; WB1 = WB mild; WB2 = WB moderate; WB3 = WB severe; WS1 = WS mild; WS2 = WS moderate; WS3 = WS severe

bution changes of each WB and WS myopathy score. The percentages of breast fillets with each WB score within each fillet weight group are shown in Figure 3. The detailed distribution is shown in Table S2 in ESM. Across all 10 weight groups, these data show changes predominantly in the distribution of breast fillets in the WB0 (normal) and WB3 (severe) categories. The highest frequency of category WB0 was found in the three lowest weight groups: 340.1 to 394.0 g (53.3%), 394.1 to 424.0 g (43.3%), and 424.1 to 442.0 g (51.6%). The percentage of WB0 category decreased in the weight group from 442.1 to 461.0 g

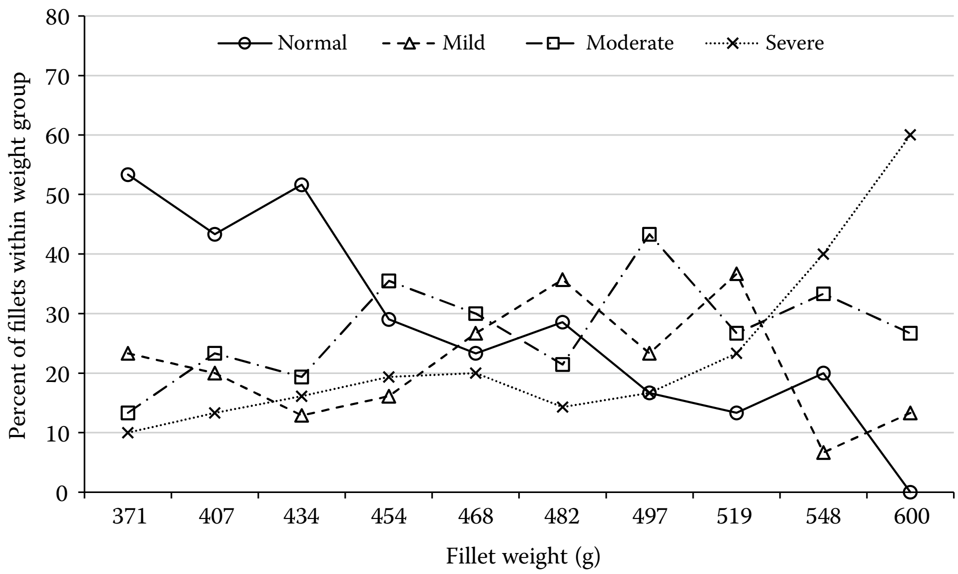

Figure 3. Percentage of breast fillet samples (n = 300) with each woody breast severity level within each of the 10 designed fillet weight groups (approximately 30 samples per each weight group)

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(29.0%). WB0 breast fillets were not found in the last weight group (570.1 to 667.5 g). The opposite trend was found in the WB3 category. An increase in the percentage of WB3 was observed in the last three weight groups: 504.1 to 533.0 g (23.3%), 533.1 to 570.0 g (40.0%), and 570.1 to 667.5 g (60.0%).

Furthermore, Figure 4 shows the percentages of breast samples with each WS score within each fillet weight group. The detailed distribution is shown in Table S3 in ESM. Similar to the WB0 category, the highest frequency of the WS0 category was found in the three lowest weight groups: 340.1 to 394.0 g (73.3%), 394.1 to 424.0 g (53.3%), and 424.1 to 442.0 g (48.4%). In contrast, the lowest percentage (20%) of WS0 was in the heaviest weight category (570.1 to 667.5 g). The occurrence of the WS1 category was high within all weight groups of breast fillets. A higher percentage of the WS2 score was found in the three heaviest weight categories of breast fillets (504.1 to 667.5 g). Across the weight categories, a small number of WS3 samples was recorded.

Relationship between the fillet weight group and the mean myopathy score of WB and WS

A linear regression model was used to determine the relationship between fillet weight (g) and selected breast myopathies. The mean WB and WS scores (dependent variables) were plotted against the mean fillet weight of each group (independent variable) (Figure 5). These results exhibited a positive linear relationship for both WB (R^2 = 0.91, P < 0.001) and WS (R^2 = 0.71, P = 0.002) myopathy with fillet weight. The mean myopathy score for WB increased from 0.80 in the 340.1 to 394.0 weight group to 2.47 in the 570.1 to 667.5 weight group. Regarding WS samples, the mean myopathy score increased from 0.33 to 1.27 for the same weight groups. Descriptive statistics for WS and WB mean myopathy scores in weight groups are shown in Tables S4 and S5 in ESM, respectively.

DISCUSSION

Myopathy scoring system

The present study evaluated the incidence of breast muscle myopathies (WS, WB, SM) in large (3.5–4 kg live weight) commercial broiler flocks. The investigation used subjective breast fillet myopathy sorting methods based on visual and tactile inspection currently used in broiler processing plants (Bowker et al. 2019; Che et al. 2022a). For more sensitive WB and WS breast fillet categorization, the present study used a 4-point scale scoring system to classify the severity of each myopathy (Malila et al. 2018; Bowker et al. 2019; Xing et al. 2020; Che et al. 2022a, b). Sirri et al. (2016) proposed a 3-point scale scoring system for SM, including normal fillets, moderate fillets

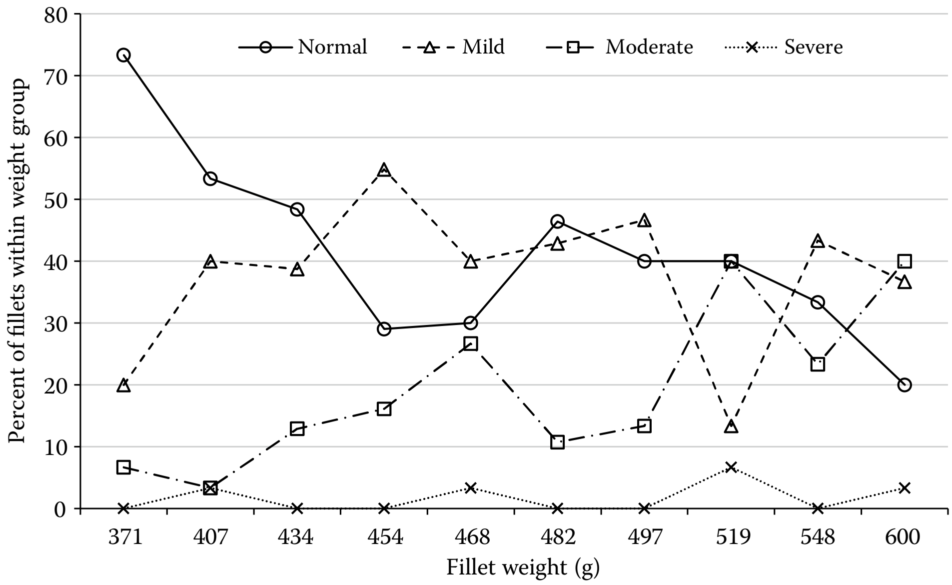

Figure 4. Percentage of breast fillet samples (n = 300) with each white striping severity level within each of the 10 designed fillet weight groups (approx. 30 samples per each weight group)

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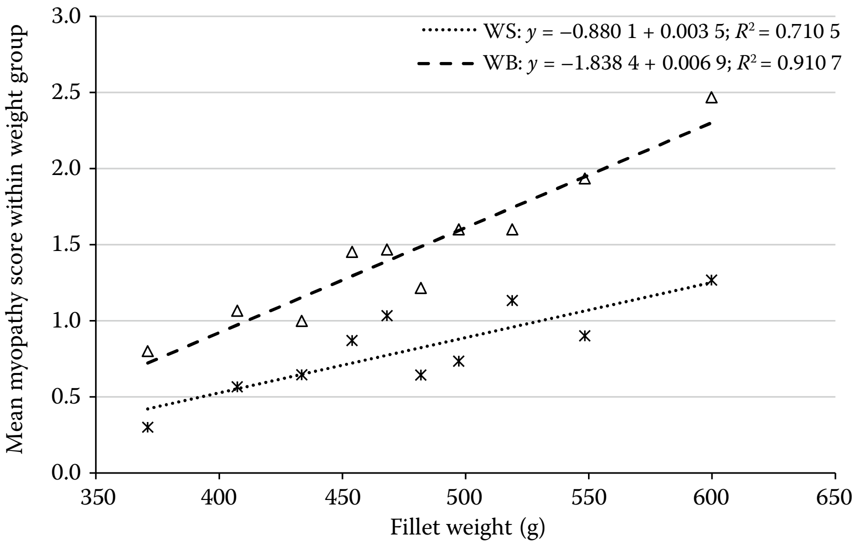

Figure 5. Relationship between each fillet weight group and mean myopathy score of woody breast (WB) and white striping (WS) Each data point represents the mean of weight group (approx. 30 samples per each data point)

with a loose structure perceivable by pinching the muscle in the cranial surface, or severe fillets showing superficial laceration. Although Zampiga et al. (2018) used this scoring system, the present study, similarly like other studies (Tasoniero et al. 2020; Che et al. 2022a, b), divided breast fillets into SM absent and SM present.

Breast myopathy distribution

The occurrence of breast muscle abnormalities is increasingly reported worldwide (Barbut 2019; Baldi et al. 2020). Based on many recent studies, it is well-known that these myopathies are associated with fast-growing genotypes of chickens selected for high breast yield (Huang and Ahn 2018; Baldi et al. 2020). However, the incidence levels can vary depending on bird age, weight at slaughter, country and the classification system used (Lorenzi et al. 2014; Sihvo et al. 2017; Petracci et al. 2019; Baldi et al. 2020).

Therefore, the present study was focused on evaluating the incidence and cooccurrence of breast myopathies in commercial fast-growing high breast-yielding broilers slaughtered at eight weeks of age. The overall prevalence rates of WS, WB, and SM found in the present study were 58.7%, 72%, and 25%, respectively. These high occurrence percentages confirm the findings across many studies around the world, as stated below. The incidence of WS is highly variable and has been reported to be as low as 12% (Petracci et al. 2013) and ranges from 43% to 98% (Kuttappan et al. 2013; Lorenzi et al. 2014; Russo et al. 2015; Tijare et al. 2016; Malila et al. 2018; Che et al. 2022a, b). A large decrease in the percentage incidence was noted from WS mild (37.7%) to WS severe (1.7%). This trend is in agreement with previous studies (Che et al. 2022a, b), even though they did not record WS3 categories. The higher incidence of WB (irrespective of severity levels) is consistent with other similar studies that found percentages ranging from 6.6% to 96.1% (Tijare et al. 2016; Dalle Zotte et al. 2017; Malila et al. 2018; Xing et al. 2020; Che et al. 2022a, b). In the present study, the incidence of WB at each severity level was in the range of 20–30%. Regarding WB2 and WB3 scores, similar findings at the 4-point scale scoring system were observed by Tijare et al. (2016), who explained the high incidence of WB based on the possible influence of controlled experimental conditions. However, our similar observations reflected incidence originating from commercial conditions. In contrast, a large difference between moderate (70.5%) and severe (11.8%) WB levels was found by Che et al. (2022b), who used 3-point scale scoring. In addition, Trocino et al. (2015) and Pascual et al. (2020) reported that WB occurrence in male broilers was higher than that in females. In contrast, Pascual et al. (2020) found a higher occurrence of SMs in females than in males. With respect to the investigation of male broilers, we could not compare these interesting findings in the present study. Regarding SM myopathy, although several studies can be found, there is still limited literature on the incidence of SM myopathy. However, the first study evaluating the incidence of SM myopathy can

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be found in the study of Sirri et al. (2016), who referred to this abnormality as a "poor cohesion defect". The same authors reported that the occurrence of mild and severe SM ranged from 35.5% to 46.9%. Our results are similar to those reported globally, wherein the incidence of SM was 21% (Baldi et al. 2020) and 35% (Zampiga et al. 2018) in Italy, and 31% (Che et al. 2022a) and 36.3% (Che et al. 2022b) in Canada.

In general, based on different study conditions, it is difficult to compare these overall occurrences with each other. Following this situation, the published data vary widely, sometimes they are even contradictory but still limited. However, based on previous literature, it can be assumed that muscle abnormalities in chicken breasts occur worldwide, where fast-growing chickens are used, and that the number is even higher than the poultry industry would allow (Petracci et al. 2019).

Cooccurrence of breast myopathies

The main aim of this research was to evaluate the combined incidence and relationship between myopathies occurring in the breast simultaneously in different severities. Historically looking at the timeline, WS myopathy was first described in 2009 (Bauermeister et al. 2009); furthermore, in 2014, WB was described as a novel myopathy by Sihvo et al. (2014), which is accompanied by white stripes. Finally, a year later, SM myopathy was described with the name "stringy or mushy breast".

Although these modern breast myopathies have begun to appear individually, in the last few years, there have been several records of simultaneous occurrence within the flock as well as within individual breast fillets. At this point, the number of the samples in the present study categorized with only WS, WB and SM myopathy was 17, 55 and 15 samples, respectively, while 67% of the affected breast fillets showed combined myopathy (Table 2). Consistent with the present findings, Che et al. (2022a) also detected more than one myopathy in 68.2% of breast samples assessed, while Che et al. (2022b) reported a cooccurrence of multiple myopathies as high as 85%. Furthermore, in the present study, approximately 66.2% of all WB samples exhibited WS myopathy. This high coexistence of WS and WB was reported across many previous studies focusing on these two myopathies. For example, Bowker et al. (2019) and Che et al. (2022a) similarly found 94.2% and 92.4% of samples affected simultaneously by WS and WB, while Che et al. (2022b) reported that only 49% of fillets were affected. However, regarding slaughter age, de Carvalho et al. (2020) reported increased WS and WB cooccurrence from 1.4% in chickens aged 4–5 weeks to 27% in chickens aged 8–9 weeks.

Currently, it is well-known that WS myopathy is often associated with WB or SM conditions, but the combined occurrence of all WS, WB and SM is poorly described. In the present study, approximately 8.7% of all assessed fillet samples (n = 300) showed combined WS, WB and SM myopathy. According to the present study, 20% of fillets were affected with SM alone, 21.3% were affected with WS, 24% were affected with WB, and 34.7% were affected with both WS and WB. In general, as the severity of the WB and WS myopathies increased, the number of samples affected by the SM condition decreased. The highest cooccurrence incidence of SM myopathy was observed when the breast fillets were affected simultaneously by WS1 and WB1 (WS1WB1SM1). Furthermore, among the samples that exhibited a WB3 degree, only one sample (WS1WB3SM1) was affected by SM myopathy. In addition, no samples were identified in the case of WS3SM1 that overlap along with any severity (0–3) of WB myopathy. These results can be compared with two different Canadian studies in which the cooccurrence of all three myopathies was reported in 22.9% of the 179 samples (Che et al. 2022a) and in 32.8% of the 9 250 samples (Che et al. 2022b). Regarding SM condition percentages, Che et al. (2022a) found only one sample affected with only SM (1.8%) and one fillet with SM and WB (1.8%), while combinations with only WS conditions were found in 21.8% of all samples affected by SM myopathy. Similarly, Che et al. (2022b) found 0.2% of single SM-affected fillets, 0.2% of SM fillets combined with WB, while fewer fillets (3.2%) were affected with only SM and WS compared with a previous study. In detail, both Canadian studies (Che et al. 2022a, b) reported that more than 74% and 90% of all SM samples were simultaneously affected with WS and WB conditions. In this context, the present study showed a higher prevalence of only SM myopathy and a lower prevalence of fillets affected with a combination of WS, WB and SM in comparison with both above-mentioned Canadian studies.

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Associations between breast myopathies and fillet weight

Two logistic regression models were built to investigate associations between all three myopathies, their severities and fillet weights. Regarding SM (Table 3), the binomial logistic regression model showed that the odds of SM presence decreased when WB severity increased to WB2 or WB3. Based on the percentages of cooccurrence distribution, this opposite relationship has already been indicated in Table 2. Furthermore, the present study did not find any statistically significant associations between SM myopathy and fillet weight. These findings are in disagreement with a recent study (Che et al. 2022a, b), which found that the odds of SM increased with fillet weight. The differences in the findings may be due to the number of samples analysed and/or the higher distribution of only SM fillets in the present study compared to Canadian studies (Che et al. 2022a, b), where more SM observations were associated with other myopathies. Che et al. (2022b) reported that broilers had higher odds of having SMs when birds were heavier than 2.45 kg at slaughter than when they were smaller than 2.30 kg.

According to the multinomial logistic regression model, WB myopathy was positively associated with fillet weight. In the present study, positive associations were also found between WB and WS myopathies. These results indicate that severe WB conditions increased the odds of WS1 and WS2. The cooccurrence of WS and WB and their severities vary widely depending on the different studies. Although these breast abnormalities share common histological features (Soglia et al. 2021), there may be multiple factors behind their relationship. Kuttappan et al. (2017) reported that the incidence of severe or very severe WS and WB conditions increased as the chickens became heavier (approx. from 2 672 g to 4 624 g) and older (from six to nine weeks of age). In that study, the relationship between WS and WB myopathies and fillet weight plateaued at nine weeks of age. Malila et al. (2018) reported WS and WB myopathies in male broilers aged six and seven weeks and recorded the predominant occurrence of mild and moderate WS samples. Furthermore, Bowker et al. (2019) reported that the incidence and degree of severity of the WS and WB conditions were positively related; however, the strength of the relationship was moderate and influenced by fillet weight, where the relationship weakened with increased fillet weight. Some recent studies have focused on the factors influencing the incidence and severity of myopathies. Aguirre et al. (2020) reported that factors, such as live weight, sex and age, were not as important as strain and fillet weight for predicting the severity of WS and WB. Different variables related to the occurrence of myopathies, such as demographics, transportation, external environmental conditions, flock health and others, were investigated in the research of Che et al. (2022b), who showed a complex and multifactorial influence on the development of myopathies.

Distribution of WB and WS myopathy scores in the fillet weight groups

For a better and more detailed understanding of the relationships between various degrees of myopathies and breast fillet weight, the present study also evaluated the percentage distributions of each WS and WB severity against the mean fillet weight of each group. Regarding WS myopathy, the percentage distribution of individual degrees across weight groups did not show any interesting trends; however, the lightest fillets had a high percentage of unaffected breasts, and the opposite finding was shown by the heaviest breasts. Similarly, in the case of WB myopathy, there is an identifiable decrease in the percentage distribution of unaffected breasts towards heavy weight groups, where the highest incidence percentage was represented by the WB3 category. These findings may be compared with a previous study conducted by Bowker et al. (2019), who observed the same trend with the distribution of unaffected WS and WB fillets in relation to increasing average weights in weight groups. Thus, it can be concluded that the heaviest weight groups had the highest percentage of the most severe degrees of WS and WB myopathies.

Relationship between the fillet weight group and the mean myopathy score of WB and WS

Finally, the linear regression model showed the impact of fillet weight on average WS and WB myopathy scores. Although both mean myopathy scores increased as fillet weight increased, different rela-

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tionships with fillet weight were found for WS and WB mean myopathy scores. Our observations are in relative agreement with Bowker et al. (2019), who reported that fillet weight had a higher impact on the average WB score than on the WS score. In addition, their findings showed a stronger quadratic relationship with fillet weight for both WS and WB in comparison with our results, where a strong relationship was found only for WB scores. However, the present study used a linear regression model and found less severe degrees of WS. In this context, both this study and Bowker et al. (2019) reported a high percentage of cooccurrence of WS and WB myopathy; thus, it is likely that the relationship between WS and fillet weight is more related to this fact.

CONCLUSION

The present study showed a very high prevalence of breast myopathies in heavy commercial chicken broilers reared under intensive production conditions. As recent studies have shown, the incidence of WS myopathy has become a common standard, which in the present study mainly co-occurred with other myopathies. It is worrisome that the present study recorded a high prevalence of WB myopathy, especially in the moderate and severe categories. The higher percentage of breast fillets was also devalued by the SM condition. Interestingly, the present study showed that if there was a severe WB category in the breast, the SM was not present. Because both WB and SM conditions have a direct impact on meat processing quality and customer perception, their high incidence between samples is alarming. The present study did not show an association between SM myopathy and breast fillet weight; however, a strong relationship between defect and fillet weight was demonstrated in WB myopathy. The present study shows that only 12% of samples were not affected with any myopathy, while 59% of breast fillets exhibited more than one myopathy. The results of the present study should lead to reflection on how to improve the current conditions in the poultry industry to reduce the incidence of myopathies and minimize the resulting losses.

Conflict of interest

The authors declare no conflict of interest.

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